Introduction

In its original meaning, 'ontology' is the study of what there is – not only of what entities exist but also of the very structure of reality. For the most part of the history of philosophy, ontology was the core of metaphysics, perhaps the major branch of philosophy. Nowadays, however, the word has different meanings and nuances. In the analytic tradition, for instance, ontology is the study not only of what there is, but also of the most general features of and the relations among what there is. This study commonly starts out from our intuitions about reality or from an *a priori* reasoning. Yet, another, increasingly growing sense of ontology has to do with reality itself in relation to our best *scientific theories*: When one asks for "the ontology of" a certain scientific theory, the question is about what reality would be like if the theory were true. Although this second meaning does not exactly match the etymology of the word (from Ancient Greek: *on*, what is; *logos*, discourse, account), the meaning drift is completely natural in the light of the fact that, at least after the Renaissance, scientific knowledge was crucial with respect to how the structure of reality and the nature of its entities were conceived.

Quantum mechanics is probably the most successful and the least understood physical theory that we have ever had. Even though this claim has become almost a cliché, its frequent repetition does not make it less true. Indeed, after almost a century of its first formulations, quantum mechanics is still posing unsolved puzzles with respect to our understanding of the microscopic world. Of course, numerous important results have been obtained during years of research, and many of them are relevant to the foundations and the interpretation of the theory. However, it is not completely clear yet how the ontology of the theory is, in particular, how reality would be if quantum mechanics were true. Not only does the question remain in force just as in the first decades of the twentieth century, but a century of philosophical and scientific discussions has brought to light that quantum reality is far more complex than originally supposed. The numerous and varied perspectives developed up to the present time just manifest this complexity. If each different perspective tells us a different story about the quantum realm, then the current variety of perspectives point out to the many "quantum worlds" we have come to conceive to date.

The aim of this volume is, precisely, to present this variety of "quantum worlds" in the most unbiased way. The different perspectives on the ontology of quantum mechanics that this volume compiles rely on different metaphysical commitments, diverse formal tools, diverging aims, or even disparate readings of the theory's formalism. All this not only makes manifest how rich and puzzling quantum mechanics is for our understanding of the physical world, but also how bridges between philosophy and physics can be built in order to make progress in such understanding. To unfold the wide variety of perspectives in an organized way, the volume is structured in five parts.

Part I, "Ontology from Different Interpretations of Quantum Mechanics," groups the chapters focusing on particular interpretations already proposed in the literature on the matter. This part opens with the chapter, "Ontology for Collapse Theories," where Wayne Myrvold claims that the natural ontology for a collapse theory is a *distributional ontology*, according to which dynamical quantities, such as charge or mass within a specified region, do not take on precise values, but rather have associated with them a distribution of values; this chapter discusses the extension of such a picture to the context of a relativistic spacetime. The second chapter, "The Modal-Hamiltonian Interpretation: Measurement, Invariance, and Ontology" by Olimpia Lombardi, draws the attention to this interpretation by exposing it in a conceptually clear and concise way, stressing its advantages both for dealing with the traditional interpretive problems of quantum mechanics and for supplying a physically meaningful account of relevant aspects of the theory. The main aim of the third chapter, "Quantum Mechanics and Perspectivalism" by Dennis Dieks, is to argue for a perspectival noncollapse interpretation that, by assigning *relational* or *perspectival* states, makes it possible to reconcile universal unitary evolution, and the resulting omnipresence of entangled states, with the occurrence of definite values of physical quantities. In the fourth chapter, "Quantum Physics Grounded on Bohmian Mechanics," Nino Zanghì rejects the interpretations based on the concepts of measurement and observer; according to him, the theory must be based on a clear *primitive ontology* that provides the spatiotemporal histories of its basic entities. In the fifth chapter, "Ontology of the Wave Function and the Many-Worlds Interpretation," Lev Vaidman undertakes a vigorous defense of this interpretation by claiming that what we see is only a tiny part of what there is: There are *multiple parallel worlds* similar to ours, and our experiences supervene on the wave function of the universe. In the sixth and closing chapter of the first part, "Generalized Contexts for Quantum Histories," Marcelo Losada, Leonardo Vanni, and Roberto Laura propose a *formalism of generalized* *contexts* for quantum histories, in which the contexts of properties at each time must satisfy compatibility conditions given by commutation relations in the Heisenberg representation; any family of histories satisfying these conditions is organized in a distributive lattice with well-defined probabilities obtained by a natural generalization of the Born rule.

Part II, "Realism, Wave function, and Primitive Ontology," is devoted to the question of realism in the quantum domain in general and, in particular, of realism regarding the wave function. In the first chapter, "What Is the Quantum Face of Realism?," James Ladyman explores the interaction between different forms of realism and different forms of quantum physics, showing the tension between usual arguments for scientific realism in the philosophy of science literature and the invocation of realism in certain interpretations of quantum mechanics. In the second chapter of this part, "To Be a Realist about Quantum Theory," Hans Halvorson takes a closer look at the distinction between realist and antirealist views of the quantum state, and argues that this binary classification should be reconceived as a continuum of different views about which properties of the quantum state are representationally significant. The final chapter of the second part, "Locality and Wave Function Realism" by Alyssa Ney, advocates for *wave function realism*, according to which the fundamental quantum entity is the wave function, understood as a scalar field on a high-dimensional space with the structure of a configuration space; according to her, this kind of realism is an attempt to explain nonlocal influences, instead of taking them as brute facts of the world.

In Part III, "Individuality, Distinguishability, and Locality," the ontological problems related to the identity and nature of quantum particles are addressed. This part begins with the chapter by Jonas Arenhart, Otávio Bueno, and Décio Krause, "Making Sense of Nonindividuals in Quantum Mechanics," which focuses on a very specific question: Assuming that quantum theories deal with "particles" of some kind, what kind of entities can such particles be? The authors respond that quantum entities are *nonindividuals* and that a metaphysics of nonindividuals requires a system of logic where the basic items have no identity. In the second chapter of this part, entitled "From Quantum to Classical Physics: The Role of Distinguishability," Ruth Kastner reviews the derivations of the classical and the quantum statistics in order to argue that a form of *separability* is a key feature of the quantum-to-classical transition; on this basis, she considers the question of what allows separability to serve as a form of distinguishability in the classical limit. The third chapter, "Individuality and the Account of Nonlocality: The Case for the Particle Ontology in Quantum Physics" by Michael Esfeld, examines different solutions to the measurement problem to conclude that the particle ontology of Bohmian mechanics provides the least deviation from the ontology of classical mechanics that is necessary so as to accommodate quantum physics, both in the case of quantum mechanics and in the case of quantum field theory. This third part closes with the chapter by Alejandro Hnilo, "Beyond Loophole-Free Experiments: A Search for Nonergodicity," where he analyzes the experiments designed to measure violations of Bell's inequalities and argues that, besides locality and realism, the measurement of the inequalities implicitly assumes the ergodic hypothesis; therefore, in order to save the validity of local realism in nature, it is necessary to search for evidence of nonergodic dynamics in Bell's experiments.

The chapters composing Part IV, "Symmetries and Structure in Quantum Mechanics," deal with structural features of the quantum theory. The first chapter of this part, "Spacetime Symmetries in Quantum Mechanics" by Cristian López and Olimpia Lombardi, stresses the relevance of symmetries to interpretation; on this basis, the authors consider the behavior of nonrelativistic quantum mechanics under the Galilean group and critically analyze the widely-accepted view about the invariance of the Schrödinger equation under time reversal. In the second chapter, "Symmetry, Structure, and Emergent Subsystems," Nathan Harshman focuses on the particular structures called *irreducible representations* of symmetry groups, in order to explore the connections between the mathematical units of symmetry embodied by those irreducible representations and the conceptual units of reality that form the basis for the interpretation of quantum theories. Finally, the third chapter of this fourth part, "Majorization, across the (Quantum) Universe" by Guido Bellomo and Gustavo Bosyk, reviews the wide applicability of majorization in the quantum realm and stresses that such applicability emerges as a consequence of deep connections among majorization, partially ordered probability vectors, unitary matrices, and the probabilistic structure of quantum mechanics.

The chapters in the fifth and final part of this volume, "The Relationship between the Quantum Ontology and the Classical World," address the classical limit of quantum mechanics from different perspectives. In the first chapter, "A Closed-System Approach to Decoherence," Sebastian Fortin and Olimpia Lombardi argue that the conceptual difficulties of the orthodox approach to decoherence are the result of its open-system perspective; so, they propose a *closed-system approach* that not only solves or dissolves the problems of the orthodox approach, but is also compatible with a top-down view of quantum mechanics. In the second chapter of this part, "A Logical Approach to the Quantum-to-Classical Transition," Sebastian Fortin, Manuel Gadella, Federico Holik, and Marcelo Losada present a *logical approach* to the emergence of classicality based on the Heisenberg picture, which describes how the logical structure of the elementary properties of a quantum system becomes classical when the classical limit is reached. In the chapter, "Quantum Mechanics and Molecular Structure: The Case of Optical Isomers," which closes the last part and the volume, Juan Camilo Martínez González, Jesús Jaimes Arriaga, and

Sebastian Fortin address the difficulty of giving a quantum explanation of chirality, that is, of the difference between the members of a pair of optical isomers or enantiomers; according to them, the solution of the problem requires an interpretation of quantum mechanics that conceives measurement as a breaking-symmetry process.

As this brief review shows, the plurality of perspectives and “quantum worlds” collected by this volume is an excellent opportunity not only to show how alive the debate on the longstanding puzzles of quantum mechanics remains, but also to present an updated state of affairs regarding our understanding of the quantum reality.